APPLICATION

FOR

UNITED STATES LETTERS PATENT

PATENT APPLICATION

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

Be it known that Kevin J. Knopp of 55 Curzon's Mill Road, Newburyport, MA 01950, Daryoosh Vakhshoori of 10 Rogers Street, Apt. 205, Cambridge, MA 02142, Peidong Wang of 225 Davis Road, Carlisle, MA 01741 and Donald L. McDaniel of 92 Prescott Street, North Andover, MA 01845, have invented certain improvements in MONOLITHIC SEMICONDUCTOR LIGHT SOURCE WITH SPECTRAL CONTROLLABILITY, of which the following description is a specification.

KK/AHURA3.CVR

AHURA-3

MONOLITHIC SEMICONDUCTOR LIGHT SOURCE

WITH SPECTRAL CONTROLLABILITY

1. Reference To Pending Prior Patent Application

This patent application (i) claims benefit of pending prior U.S. Provisional Patent Application Serial No. 60/440,115, filed 01/15/03 by Kevin Knopp et al. for MONOLITHIC SEMICONDUCTOR LIGHT SOURCE WITH SPECTRAL CONTROLLABILITY (Attorney's Docket No. AHURA-3 PROV) and (ii) is a continuation-in-part of pending U.S. Patent Application Serial No. 10/632,779, filed 08/01/03 by Daryoosh Vakhshoori et al. for SYSTEM FOR AMPLIFYING SIGNALS (Attorney's Docket No. AHURA-1), which two patent applications are hereby incorporated herein by reference.

2. Field Of The Invention

This invention relates to optical systems in general, and more particularly to systems for amplifying optical signals.

AHURA-3

3. Background Of The Invention

3.1 In General

Dense wavelength-division multiplexing (DWDM) is currently the preferred method for satisfying bandwidth demand for fiber-optic long-haul transport in telecommunication systems. As the optical data signal travels through the fiber, however, fiber nonlinearities, fiber loss, and amplified spontaneous emission (ASE) all act to degrade the signal-to-noise ratio of the data signal. As a result, the optical signal needs to be periodically amplified and eventually electrically regenerated so as to maintain the signal integrity.

The design of an economical DWDM network has to consider performance versus cost for all of the network elements such as transmitters, amplifiers, regenerators, add/drop nodes, receivers, etc. To save expense on the amplifiers, for example, the length of the amplifier span should be as long as possible. Extended amplifier span, however, results in high ASE

AHURA-3

accumulation from low input to amplifiers, and/or large nonlinear effects due to the use of high launch power. This degradation in turn demands more frequent optical-to-electrical-to-optical (OEO) regeneration. A

5 typical 40 channel DWDM system using Erbium-doped fiber amplifiers (EDFA's) generally has an amplifier span spacing of about 80 km and OEO regeneration distances of around 500-600 km.

Currently, OEO regeneration is responsible for a

10 much larger percentage of overall system cost than amplifiers. It is, therefore, desirable to extend the regeneration distance wherever possible.

Raman fiber amplifier technologies have emerged as a highly promising building block to allow DWDM

15 transmission for distances greater than 1500 km without OEO regeneration. This is particularly important inasmuch as the majority of data traffic on a telecommunications network typically has a destination distance which exceeds 1000 km.

20 Raman fiber amplifiers generally use the transmission fiber itself as the gain medium. Thus, the signal passing through the fiber is amplified as it

AHURA-3

propagates. Because of their distributed nature, Raman amplifiers present several significant advantages over EDFA technologies:

(1) Since the Raman amplification makes the fiber partially transparent, a high signal-to-noise ratio can be maintained over multiple span distances.

(2) For the same reason, the nonlinear effects can be significantly reduced since the maximum signal power in the fiber can be significantly reduced.

(3) The Raman gain profile of optical fiber is much broader and smoother than that of EDFA's. As a result, the combination of several pump laser wavelengths can provide overall gain profiles as broad as near 100 nm with less than 1 dB gain ripple, thus reducing the gain ripple and tilting effects generally associated with EDFA's.

(4) Inline EDFA's typically operate in saturation mode where the gains of the amplifier for individual wavelength channels are a function of total input signal power. As a result, when an optical channel is added or dropped from the fiber, the gains for all of the other channels change, causing network transients,

AHURA-3

distortions and misbalances. By contrast, Raman amplifiers typically work in a linear mode where the gain of each channel is independent of all of the other channels. Thus, dynamic wavelength adds/drops in a Raman system have less of an effect on overall system performance.

Raman-assisted transmission generally compares favorably to EDFA-only systems, leading to better system quality factors, longer amplifier spans, and hence longer DWDM transmission before the need for OEO regeneration.

One evolving application area of Raman amplifiers, beyond the traditional long-haul transmission application discussed above, is in the hybrid fiber coaxial cable (community antenna) TV (HFC-CATV) industry. HFC-CATV, using subcarrier multiplexing (SCM) and multilevel quadrature amplitude modulation (QAM) technology, generally requires >50 dB carrier-to-noise ratio and high suppression of inter-modulation, second order and third order distortions, which generally calls for high optical power and low noise accumulation. Currently, this is

AHURA-3

typically achieved by employing high output power
EDFA's (up to 25 dBm) and limiting span spacing
(typically 30-40 km) and amplifier stages. However, by
using distributed Raman amplification, it is possible,
due to the low noise figure (NF) and in-fiber Raman
amplification, to extend the span spacing, add
amplifier stages and lower input power without
significantly compromising system performance.
However, applications of Raman amplifiers in the CATV
industry are currently impaired by cost.

Improvements in Raman amplification would also
have advantageous applications in a wide range of
instrumentation and imaging applications.

3.2 Principles Of Raman Amplification

The principles of Raman amplification in fiber are
based on the process of stimulated Raman scattering
(SRS). When an optical beam of frequency ω_P is
injected into, and propagates along, an optical fiber,
a small fraction (typically 10^{-6}) of the incident
photons are scattered by the molecules to lower-
frequency ($\omega_S < \omega_P$) states while, at the same time, the

AHURA-3

molecule makes a transition between vibrational states. The incident light acts as a pump to generate the frequency down-shifted (ω_S) light, which is sometimes called

5   Stokes waves. If a signal at the frequency ω_S is coincident with the pump beam (at frequency ω_P) in the fiber, the signal will be amplified by the Raman scattering-induced Stokes waves (also at frequency ω_S).

One outstanding feature of fiber Raman amplifiers

10   is that the Raman gain profile of standard fused silica fiber is very broad due to the amorphous nature of the glass. Typically, the Raman gain increases nearly linearly from the pump frequency towards a maximum at about 13.2 THz (100 nm) and then falls off fairly

15   sharply. For example, if a high power 1450 nm laser is injected into a 40 km standard single mode fiber such as Corning SMF-28^{TM} fiber, the Raman gain profile will have a maximum near 1550 nm, with a usable gain bandwidth of ~30 nm (see Fig. 1).

20   The magnitude of the Raman gain in optical fiber depends on the respective compositional doping elements. The normalized gain spectral shape, however,

AHURA-3

is much less sensitive to glass composition for most fibers typically used.

In the first order approximation, the Raman gain increases nearly linearly, in dB, with increasing pump power. Nearly 10 dB of Raman gain is typical for 500 mW of pump power injected into 40 km of Corning SMF-28™ fiber. The upper limit of realistically useful Raman gain is generally limited by the double Rayleigh scattering process. At that upper limit, the Rayleigh back scattering causes multiple reflections of both the ASE and the signal, thus causing performance degradation of the transmission. Double Rayleigh scattering becomes prominent as the Raman gain reaches above 15 dB.

Due to the fact that the Raman gain profile is determined by the pump laser wavelength, the Raman gain spectrum can be tailored in shape and width by selecting the appropriate pump laser wavelength spectrum. For telecommunication applications, it is common to combine a number of high power diode lasers, each with a different wavelength, to collectively yield a broad and flat gain profile so as to accommodate the

AHURA-3

transmission window of interest. To construct a 100 nm

bandwidth Raman amplifier, up to 8 pump wavelengths,

ranging from 1430 nm to 1520 nm, are needed for the

amplification of signals in the 1530 nm to 1620 nm band

5   with less than 1 dB gain ripple. The 1 dB gain ripple

is due in part to the fine and sharp structures near

the peak of the gain profile shown in Fig. 1.

One significant characteristic of Raman amplifiers

is that Raman amplification is effective only if the

10   signal beam has the same polarization as that of the

pump. To obtain a polarization-insensitive Raman

amplifier, two diode lasers, with orthogonal

polarization, are generally used for each pump

wavelength. Alternatively, another approach to solve

15   this issue is to use various polarization scrambling

techniques. However, current polarization scrambling

techniques are generally relatively costly and bulky,

and have unproven reliability.

Another important issue for distributed Raman

20   amplification is the relative intensity noise (RIN)

transfer from the pump laser to the signal. Raman

scattering, due to its fast response time, causes

AHURA-3

amplitude noise in the pump lasers to be proportionally

transferred to the gain fluctuations. As is

schematically shown in Fig. 2, when a noise-free signal

beam propagates along the Raman amplified transmission

5   fiber, the signal data set experiences a time-dependent

amplification. As a result of this phenomena, the

output signal beam carries amplitude noise.

The noise transfer from pump laser to the signal

beam depends on the pump geometry employed.

10   More particularly, if the pump propagates in the

direction opposite to that of the signal, the signal

beam experiences the gain through its entire traveling

time in the fiber, and the RIN of the pump laser is

then effectively averaged over the travel time. For a

15   fiber length of 20 km, the signal beam traveling time

is about 100 microseconds. The high frequency RIN

components, typically above 1 MHz, are substantially

insensitive to the signal transmission quality (Fig.3).

This suppression of the RIN transfer from pump to

20   signal is one of the main reasons that "backward

pumping" remains the most popular scheme for Raman

amplification in telecommunication systems.

AHURA-3

On the other hand, when a forward pump scheme is employed so as to provide a co-propagating pump and signal, the average of the pump RIN is determined only by the walk-off time between the signal and pump

5   generated by dispersion of the fiber. The RIN transfer from pump to signal remains effective for much higher frequency components, as shown in Fig. 3. The RIN of the pump lasers must then generally be limited to <-150 dB/Hz. This requirement is often difficult to

10 achieve for the commonly-used frequency-stabilized Fabry-Perot lasers. To achieve such low RIN, distributed feedback (DFB) lasers have generally been used for forward pumping applications. A disadvantage of using DFB lasers as a Raman pump, however, is that

15 the narrow linewidth of a DFB laser causes significant Brillouin back-scattering at a power level much lower than that needed for the Raman pump. As a result, linewidth broadening techniques need to be applied to suppress the Brillouin scattering while keeping the RIN

20 within the required range.

When multiple high power diode lasers are used as the Raman pumping source, nonlinear interactions

AHURA-3

between the various pumps becomes an important design consideration. When the frequencies of the pump lasers vary over 100 nm, the pumps at high frequency can effectively amplify the pumps at lower frequencies (see

5   Fig. 4), causing nonlinear power evolution of the pumps inside the fiber. In addition, four-wave-mixing between pumps can create side bands with frequencies extending into the signal band. This causes an excessive noise floor for certain signal channels.

10   Generally, distributed Raman amplifiers are currently associated with high cost because of their sophisticated design, expensive high power diode lasers and complex packaging. More fundamentally, technical limitations such as pump-pump nonlinear interactions

15   and gain ripple are inherently associated with the use of multiple high power diode lasers to provide a relatively broad and flat gain profile.

4. Summary Of The Invention

20   The present invention provides solutions to a number of the challenges described above.

AHURA-3

More particularly, in one form of the invention, there is provided a system for amplifying optical signals comprising: an optical fiber for carrying the optical signals; a high power broadband light source;

5   and a connector for introducing the high power broadband light source into the optical fiber as a Raman pump so as to induce Raman amplification of the optical signals within the fiber.

In another form of the invention, there is

10   provided a method for amplifying optical signals comprising: introducing a high power broadband light source into an optical fiber carrying the optical signals so that the high power broadband light source acts as a Raman pump so as to induce Raman

15   amplification of the optical signals within the fiber.

And in another form of the invention there is provided a spectrally filtered high power broadband light source comprising a spectrally filtered amplified spontaneous emission (ASE) generated from an optical

20   component.

AHURA-3

5. Brief Description Of The Drawings

These and other objects and features of the present invention will be more fully disclosed or rendered obvious by the following detailed description

5   of the preferred embodiments of the invention, which is to be considered together with the accompanying drawings wherein like numbers refer to like parts and further wherein:

Fig. 1 is a schematic diagram showing the

10   normalized Raman gain spectrum of standard single mode fiber, at a pump wavelength of 1450 nm;

Fig. 2 is a schematic diagram showing distributed Raman amplification using forward pumping;

Fig. 3 is a schematic diagram showing the RIN

15   transfer spectrum for a co-pumped and counter-pumped Raman amplifier with 10 dB of gain;

Fig. 4 is a schematic diagram showing the power evolution of pump diode lasers along the fiber path;

Fig. 5 is a schematic diagram showing the

20   simulated Raman gain shape achieved using (i) six discrete pump wavelengths, and (ii) two broadband light sources;

AHURA-3

Fig. 6 is a schematic diagram showing depolarizers for long and short coherence light sources;

Fig. 7 is a schematic diagram showing the reduction of FWM achieved in a Raman amplifier pump using (i) discrete pump wavelengths, and (ii) a broadband ASE source;

Fig. 8 is a schematic diagram showing a broadband ASE Raman pump source;

Fig. 9 is a schematic diagram illustrating how multiple ASE sources can be superimposed so as to form a composite ASE spectrum for Raman pumping;

Fig. 10 is a schematic diagram illustrating a first preferred embodiment for forming a broadband ASE source;

Fig. 11 is a schematic diagram illustrating a second preferred embodiment for forming a broadband ASE source;

Fig. 12 is a schematic diagram illustrating a third preferred embodiment for forming a broadband ASE source;

AHURA-3

Fig. 13 is a schematic diagram illustrating a fourth preferred embodiment for forming a broadband ASE source;

Fig. 14 is a diagram showing the use of a discrete seed and booster to generate high power ASE;

Fig. 15 is a schematic diagram illustrating a fifth preferred embodiment for forming a broadband ASE source;

Fig. 16 is a schematic illustration showing a booster power module (BPM) simulated transverse mode shape of an asymmetric optical confined ridge waveguide;

Fig. 17 is a schematic illustration showing a finite element simulation of the temperature distribution of a booster waveguide;

Fig. 18 is a schematic diagram of a MMI power combiner;

Fig. 19 is a schematic illustration of a wet etched InP based booster amplifier ridge waveguide;

Fig. 20 is a schematic diagram of a holographic lithography system;

AHURA-3

Fig. 21 is a schematic diagram showing a broadband light source configuration with seed wavelength control based on thin-film filters;

Fig. 22 is a schematic diagram showing simulated transmission of a multicavity thin-film notch filter used for seed wavelength control;

Fig. 23 is a schematic diagram showing measured performance obtained using a discrete seed and booster as shown in Fig. 21 for ASE generation; and

Fig. 24 is a schematic diagram showing a measured ASE spectrum at 100mW of output power from the booster waveguide shown in Fig. 21.

6. Detailed Description Of The Preferred Embodiments

6.1 The Use Of Amplified Spontaneous Emission (ASE) As A Raman Pump Source

In accordance with one aspect of the present invention, a high power broadband light source is used as a high power Raman pump source to facilitate the amplification of optical signals.

AHURA-3

In one preferred form of the invention, the high power broadband light source is generated from spectrally filtered amplified spontaneous emission (ASE) from various semiconductor or fiber sources.

The use of a high power broadband light source as a Raman pump source has inherent performance advantages in the areas of gain ripple and flatness, nonlinear pump-to-pump interactions, pump-to-signal interactions, and in the methods of depolarization.

6.1.1 Gain Ripple And Flatness

To extend the amplification bandwidth in Raman amplifiers, it is a straightforward approach to multiplex a number of pump lasers (each with a different pump wavelength) to reach the desired gain bandwidth. The excited gain spectrum is a convolution of the pump spectrum and the Raman gain shape shown in Fig. 1. For each pump wavelength, the Raman gain profile (Fig. 1) shows a sharp feature near the peak of the Raman gain. The severity of this feature depends to some extent on the composition of the fiber, and hence on the fiber type. To eliminate this ripple,

AHURA-3

pump lasers must be spaced such that the frequency

difference between adjacent pumps is less than the

bandwidth of the ripple. Given the fact that high

power diode lasers are expensive, as is the packaging

5   of multiple diodes, the number of diode lasers used,

and the distribution of their wavelength spacing, has

to be designed so as to achieve maximum bandwidth, and

minimum gain tilt and ripple, within feasible cost.

Fig. 5 illustrates the gain profile of a typical design

10   using 6 discrete pump wavelengths distributed across

80 nm. The gain ripple of 0.5 dB is observed. Further

reduction of the gain ripple can generally be achieved

only if the pump wavelength spacing is reduced to less

than 2 nm. Thus, an unfeasibly large number of pump

15   lasers are needed to cover the 80 nm bandwidth.

Significantly, however, if a broadband high power

ASE source is used as the Raman pump instead of the

multiple discrete wavelength lasers, a large reduction

in gain ripple is observed. The solid curve in Fig. 5

20   illustrates the results when two broadband pump sources

are used to yield a nearly perfectly smooth gain

profile. The smoothness of the gain ripple is a direct

AHURA-3

result of the physical convolution "like" process between the pump source spectrum and the Raman response function of the optical fiber. The overall flatness of the achieved gain can be controlled by selecting the proper spectral profiles (i.e., wavelength and power distribution) of the broadband pump sources.

6.1.2 Depolarization

As noted above, Raman gain is highly polarization dependent. Amplification of the signals is essentially only realized along the same polarization direction as the polarization of the pump. To reduce the polarization-dependent gain, the solution is to provide a depolarized pump source. In current Raman pump modules, this is generally accomplished in one of two ways.

The most common approach is to use two semiconductor lasers for each wavelength desired, each with orthogonal linear polarizations. This technique also allows the total pump power to be distributed amongst two lasers rather than one. However, inasmuch as each laser ages independently, there is concern

AHURA-3

about the degradation of the polarization-dependent gain over the life of the amplifier.

The second approach is often used when the laser output power of a single laser diode is sufficiently high to supply Raman gain for both polarizations. In this alternative approach, a depolarizer is used to create two orthogonal linear polarizations. This depolarizer may be a passive depolarizer comprising a long length of optical fiber (e.g., ~10 m), where the single linear polarization state of the high power laser is split into two orthogonal linear components, delayed, and then recombined into one beam. To obtain two independent orthogonally-polarized beams, it is important that the delay length should be greater than the coherence length of the source or an elliptical polarization state will be formed when recombined. Thus, the long length of the optical fiber depolarizer is necessary when depolarizing a semiconductor laser with an optical fiber depolarizer so as to provide the appropriate delay for the long coherence length of the semiconductor laser.

AHURA-3

Significantly, the coherence length of broadband ASE is inherently shorter than a semiconductor laser by about 3 orders of magnitude (e.g., it is only ~1 mm). This is because the incoherence of the source allows a

5   much shorter delay length. Consequently, the depolarizer for broadband ASE can be constructed from a compact series of bulk optical components. Fig. 6 is a schematic diagram of exemplary optical elements, and a pictorial illustration of the polarization state, for

10   depolarizing short and long coherence light sources. The small size of the optical elements and their spacing allows them to be readily integrated into the package of the high power broadband Raman pump source.

15   ## 6.1.3 Nonlinear Interactions And Beat Noise

As the optical power injected into fiber increases, nonlinear optical effects, such as Self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), can become an

20   important source of noise. The nonlinear optical interaction can originate from the signal channel as well as from the pump lasers. The relative importance

AHURA-3

of these effects depends on the particular system design parameters such as power per channel, channel spacing, the total number of channels and fiber dispersion. For multi-wavelength pumped Raman

5   amplifiers, one particularly important nonlinear effect is four-wave mixing between pump lasers. This can be especially detrimental as the amplifier bandwidth approaches the Raman gain peak shift (i.e., ~100 nm).

When n lasers with discrete laser frequencies

10   $(\omega_{P1}...\omega_{Pn})$ are used for pumping the optical fiber, FWM generates side bands at $\omega_{FWM}=\omega_{Pi}+\omega_{Pj}-\omega_{Pk}$, with i, j, k=1, 2...n. With all of the i,j,k combinations possible, the FWM side bands are distributed between frequencies of $\omega_{P1}-\Delta_P$ and $\omega_{Pn}+\Delta_P$, where $\Delta_P=(\omega_{Pn}-\omega_{P1})$ is

15   the frequency range of the pump lasers. The strength of the FWM sidebands at $\omega_{FWM}=\omega_{Pi}+\omega_{Pj}-\omega_{Pk}$ is proportional to $|P_iP^*_jP_k|^2$. For broadband Raman amplifiers, where Δ_P approaches 100 nm, the FWM sidebands on the low frequency (long wavelength) side can fall within the

20   signal window of the frequencies of the amplifier. This effect can be observed in forward, as well as backward, pumped Raman amplifier configurations. In

AHURA-3

backward pumped configurations (i.e., with signal and pump counter-propagating), the FWM parasitic signal is redirected into the signal direction through Raleigh scattering. If the parasitic FWM signal falls within

5 the receiver bandwidth of a practical signal channel, the quality of the transmission within that channel is seriously degraded.

The system quality as a whole is limited by the worst case of all the signal channels.

10 In connection with the present invention, it has been found that overall system performance can be much improved if the pump source has a continuous broadband distribution. This is because when the total optical power is unchanged, the FWM sidebands are redistributed

15 over a large number of signal channels, rather than where the FWM side bands are being concentrated over a few signal channels. Fig. 7 illustrates the reduction of FWM achieved in a Raman amplifier pump with a broadband ASE source (see the schematic "b" in Fig. 7)

20 as compared to a Raman amplifier pumped with discrete wavelengths (see the schematic "a" in Fig. 7).

AHURA-3

6.1.4 Raman Gain Beating

In addition to the degradation of an amplifier's noise characteristics due to nonlinear phenomena, linear mechanisms can also be responsible for degradation. One such linear mechanism is Raman gain beating which is caused by a coherent beat frequency located between longitudinal modes of a Fabry-Perot laser cavity. For a 1 mm laser cavity length, the mode spacing is approximately 3 angstroms. This corresponds to a 40 GHz coherent beat frequency. This coherent beating is particularly detrimental to the noise figure in the forward (i.e., pump and signal co-propagation) Raman amplifier configuration. Significantly, in the case of a broadband ASE pump source, the lack of coherence of the source substantially completely eliminates Raman gain beating.

6.2 High Power Broadband Semiconductor ASE Source

6.2.1 Spectrally Filtered High Power
Broadband ASE Source In General

AHURA-3

The broadband light source used as the Raman pump source can be generated from any light which has a sufficiently broad and intense emission spectrum. Such light sources can be formed, for example, from amplified spontaneous emission (ASE) of rare earth doped optical fiber, planar waveguides, or semiconductor optical amplifiers. Further examples are spectrally broadened multimode semiconductor lasers or multiorder cascaded Raman lasers. These latter examples (i.e. spectrally broadened multimode semiconductor lasers and multiorder cascaded Raman lasers) have previously been used as Raman pump sources, but with an emphasis on their use for suppressing stimulated Brillouin scattering and, significantly, the spectral broadening is generally limited to no more than a couple of nanometers.

This document will hereinafter concentrate on methods and apparatus for providing a high power broadband light source using amplified spontaneous emission (ASE) from semiconductor optical amplifiers. However, it will be appreciated by those skilled in the art that these same methods and apparatus can be

AHURA-3

applied in principle to ASE generated from other laser gain medium.

Fig. 8 illustrates a schematic block diagram of a broadband ASE source in combination with spectral filtering to achieve a desired spectral distribution for the Raman pump. Gain profile shaping can be effected by wavelength filtering, within or outside the active devices, in a dynamic or static fashion. Thin-film filters or Bragg gratings can be used for such wavelength filtering.

One of the most promising and economical solutions for making high power broadband ASE sources is high power semiconductor devices with a specifically designed waveguide structure and facet coating.

The broad optical spectrum can be provided by a single ASE source or a superposition of multiple narrower bandwidth (e.g., 3-40 nm) ASE sources. These narrower bandwidth ASE sources can be multiplexed together in a continuous or discontinuous fashion as illustrated in Fig. 9 so as to form a composite ASE source. In this manner, gain flatness control can be achieved through the control of the total pump

AHURA-3

spectrum, where total pump spectrum control is in turn
achieved through the control of the contribution of the
relative intensity of each narrower bandwidth ASE
source.

5   A high power broadband ASE source can also be used
for purposes other than Raman amplifiers, e.g., as
light sources for general instrumentation (including
for example fiberoptic gyros), imaging (including, for
example, medical imaging), and semiconductor analysis
10   applications. These applications can benefit since
relatively high power can be achieved without the
complication of laser speckle resulting from its
temporal coherence; however, the waveguide nature of
the source provides spatial coherence, thus allowing
15   spatial manipulation of the output as efficiently as a
laser beam. Additionally, the relative intensity noise
of this source has been shown to be as good as the best
semiconductor laser.

20   6.2.2 Semiconductor Embodiments In General
          This section describes the semiconductor chip
design, fabrication, and packaging considerations for

AHURA-3

realizing such a device. The semiconductor material

system used depends to a large extent on the wavelength

of the desired application. Among others, material

systems such as AlAs, GaAs, InP, GaP, InGaAs, InGaAsP,

5   InAlGaAs, and GaN can be used.

The basic principle of device operation is the

amplification of a seed spectrum of amplified

spontaneous emission (ASE) along the length of a

semiconductor waveguide containing one or more active

10   regions which are biased above transparency. The

manner in which the seed light is generated and shaped

(i.e., filtered), the number of waveguides used, the

number of sections the waveguides are comprised of, the

optical bandgap and electrical bias of those sections,

15   and the method of multiplexing multiple waveguides, all

have various preferred embodiments which will be

described below.

6.2.2.1 First Embodiment

20   Fig. 10 is a schematic diagram of a semiconductor

die 100 used in a first preferred embodiment. The die

100 consists of a serial connection of a wavelength

AHURA-3

seed section 103 and a power booster or power
amplification section 106 formed along a semiconductor
waveguide 109.

The wavelength seed section 103 preferably
comprises multiple subsections 103A, 103B, 103C, etc.
formed along the semiconductor waveguide 109. Three
subsections 103A, 103B, 103C are shown in Fig. 10;
however, it should be appreciated that this number is
merely exemplary and more or less than this number of
wavelength seed subsections may be used. The gain
profile within each subsection 103A, 103B, 103C, etc.
is chosen so as to provide ASE in a particular
wavelength range. The gain profiles can be defined in
each subsection 103A, 103B, 103C, etc. by such
techniques as epitaxial regrowth or quantum well
intermixing. The quantum well blocks of these
subsections are designed to provide a region of high
gain with, for example, 3-10 quantum wells.

A high reflectance mirror 112 is used to capture
and redirect the portion of seed light traveling away
from the power booster section 106. The spectral
profile of this mirror 112 is designed to provide the

AHURA-3

desired nominal ASE spectrum at the input of the power booster section 106. This high reflectance mirror 112 can be defined through thin film coating of the cleaved semiconductor facet or by incorporating a distributed Bragg reflector along the waveguide. Each wavelength seed subsection 103A, 103B, 103C, etc. has an independent electrical contact to allow dynamic tailoring of the seed light spectrum prior to launching into the power booster section 106. The output power of the wavelength seed section 103 can range from 1 to 20 mW, although it is not limited to this range.

The power booster section 106 is designed to amplify the broad spectrum (20-100 nm) of ASE seed light and generate power in excess of 500 mW. This can be accomplished through the use of a long waveguide section 109A which is optimized for low loss rather than high gain. Reducing the number of quantum wells to the range of 1 to 5, reducing optical confinement in p-doped cladding, and increasing the confinement factor in n-doped cladding (which has lower free carrier absorption loss) will all reduce the loss. Additionally, the quantum wells must provide gain

AHURA-3

across the entire wavelength range of the seed light.
This can be accomplished through chirping of the
thickness of the quantum wells in the vertical
direction. For example, the upper quantum well

5   provides shorter wavelength gain while the lower two
quantum wells provide longer wavelength gain.

An angled waveguide 109B is used at the output of
the power booster section 106, followed by an
antireflection coating 115 on the semiconductor facet.

10   This combination is used to eliminate feedback into the
power booster section 106 and to prevent distortion of
the broadband spectral profile from Fabry-Perot
interference.

As is the case for all of the embodiments

15   discussed herein, the output will be highly linearly
polarized because of the polarization dependence of the
quantum well gain or, in the case of bulk active
region, excess loss of TM over TE mode. If two equal
components of linear orthogonal polarization are

20   desired for applications such as Raman amplifiers, the
construction described in Fig. 6(b) can be used.

The advantages of the construction shown in

AHURA-3

Fig. 10 include: full semiconductor integration, serial
multiplexing, compatibility with dynamic spectral
flattening, and reduced packaging complexity, among
others.

6.2.2.2 Second Embodiment

Fig. 11 is a schematic diagram of a semiconductor
chip 200 and optical train 203 used in a second
preferred embodiment. Although multiple chips can be
used, this embodiment will be described in the context
of a single chip 200 comprising an array of parallel
waveguides 206, where the array comprises a plurality
(e.g., 2 to 10) of parallel waveguides 206A, 206B,
206C, etc. The gain profile (i.e., peak wavelength and
shape) of each waveguide 206A, 206B, 206C, etc. is
chosen so as to provide the ASE output in a particular
wavelength range (e.g., 3-30 nm).

The gain profiles can be defined within each
waveguide 206A, 206B, 206C, etc. by employing such
techniques as epitaxial regrowth, quantum well
intermixing or other techniques known in the art. The
spectral width and intensity of the ASE emitted from
each waveguide 206A, 206B, 206C, etc. can be tailored

AHURA-3

through the design of the active region, the length of

the waveguide, and active adjustment of the current

injected into each waveguide. The quantum well block

of each waveguide is designed to provide a region of

5 high gain with, for example, 3-10 quantum wells, along

the first 0.3 μm to 1 mm length of the waveguide. The

remainder of the waveguide is optimized for low loss

rather than high gain so as to amplify the ASE seed

light and generate power in excess of 200 mW. To

10 achieve low loss, the number of quantum wells is

preferably reduced to the range of, for example, 1 to

5, and the doping in the waveguide cladding can be

reduced. A high reflectance mirror 209 is provided at

one end of the waveguide, and angled waveguides 212A,

15 212B, 212C, etc. used at the output, followed by a

facet antireflection coating 215. This combination is

used to eliminate feedback into the power booster and

prevent distortion of the broadband spectral profile

from Fabry-Perot interference.

20 The waveguide design of this second embodiment

differs from the first embodiment (Fig. 10) discussed

above in that each waveguide 206A, 206B, 206C, etc.

AHURA-3

only needs to produce power in a narrower spectral
range (e.g., 3-30 nm). The power and spectral width of
each waveguide 206A, 206B, 206C, etc. are then
multiplexed using the optical train 203 contained

5   within the hermetically sealed package.

The optical train 203 comprises a polarization
multiplexer 218 for each pair of waveguides 206A, 206B,
206C, etc., followed by a wavelength multiplexer port
221 for each pair of multiplexers 218. Fig. 11

10   illustrates this multiplexing principle for 4
waveguides using two polarization multiplexers 218 and
a two-port wavelength multiplexer 221.

The advantages associated with the construction
shown in Fig. 11 include: redundancy, compatibility

15   with dynamic spectral flattening, compatibility with
cooler-less operation, and a lower optical power
requirement per waveguide, among others.

6.2.2.3 Third Embodiment

20 .   Fig. 12 is a schematic diagram of a semiconductor
chip 300 and optical train 303 used in a third
preferred embodiment. The die 306 consists of a

AHURA-3

wavelength seed section 309 which is power multiplexed by a multiplexer 312 into a long low loss power amplification (or booster) waveguide 315. Wavelength seed section 309 preferably comprises a plurality of wavelength seeds 309A, 309B, 309C, etc. Both the seed light waveguides 309A, 309B, 309C, etc. and the power booster waveguide 315 are designed for broadband ASE emission, just as in the first embodiment (Fig. 10) discussed above. A high reflectance mirror is provided for each of the seed waveguides 309A, 309B, 309C, etc. These mirrors may be independent of one another, or they may be different sections of a single mirror, such as is shown in Fig. 12 with the high reflectance mirror 318. The reflectivity profiles of the high reflectance mirror for each seed waveguide 309A, 309B, 309C, etc. are optimized to provide the correct seed light profile for control of the output ASE spectrum. The power booster waveguide 315 includes an angled end 321 and an anti-reflectance coating 324 at its output end. Spectrum function controls such as tilt can be achieved through the appropriate mix of seed light functions.

The advantages of the construction shown in

AHURA-3

Fig. 12 include: redundancy, and reduced control circuit complexity, among others.

6.2.2.4 Fourth Embodiment

Fig. 13 is a schematic diagram of a semiconductor die 400 and optical train 403 used in a fourth preferred embodiment. The semiconductor die 400 consists of an array of, for example, 2 to 10, parallel waveguides 406A, 406B, 406C, etc., each with a narrowband wavelength reflector (e.g., 3-10 nm) to define the seed light bandwidth for each waveguide 406A, 406B, 406C, etc. A plurality of discrete reflectors, each formed independent of the others, may be provided; or the reflectors may be different sections of a single reflector, such as is shown in Fig. 13 with the reflector 409. The reflector (as in all of the foregoing embodiments) can be formed, for example, by thin-film deposition, an etched semiconductor distributed Bragg reflector (DBR), or an abutted glass planar light wave guide/grating. Fig. 13 illustrates the use of a planar light wave circuit grating to form the reflector 409. The attributes of

the power waveguides 406A, 406B, 406C, etc. are

substantially the same as disclosed in the second

embodiment (Fig. 11) discussed above. The outputs of

the waveguides 406A, 406B, 406C, etc. are wavelength

5   combined using a thin-film edge-filter multiplexer 412.

The multiplexer 412 is preferably formed using a glass

substrate 415 with a series of patterned edge-filters

418 deposited by thin film deposition.

The advantages of the construction shown in

10   Fig. 13 include: compatibility with dynamic spectral

flattening, and lower optical power requirement per

waveguide, among others.

6.2.2.5 Fifth Embodiment

15   Fig. 14 is a schematic diagram of a high power

spectrally filtered ASE source 500 which comprises a

fifth embodiment of the present invention. ASE source

500 comprises a discrete seed 505 and booster 510 which

are used to generate high power ASE. More

20   particularly, an isolator 515 is positioned between

seed 505 and booster 510, and a mirror 520 is

positioned between isolator 515 and booster 510. A

AHURA-3

lens 525 is positioned between seed 505 and isolator

515, a lens 530 is positioned between mirror 520 and

booster 510, and a lens 540 is positioned at the output

of booster 510. In this construction, spectrally

5   filtered ASE light is produced in seed 505, it is

passed through lens 525 and isolator 515, reflected off

mirror 520, passed through lens 510 and into booster

510, where it is amplified, and then passed out lens

540.

10

6.2.2.6 Sixth Embodiment

Fig. 15 is a schematic diagram of a spectrally

controllable light source device 600 which comprises a

sixth embodiment of the present invention. Spectrally

15 controllable light source 600 consists of a waveguide

seed section 605 which is coupled by a broadband power

combiner 610 into a long single-mode high-power

"booster" waveguide 615. Waveguide seed section 615

comprises a plurality of wavelength seeds 605A, 605B,

20 605C, 605D, etc. Both the seed light waveguides 605A,

605B, 605C, 605D, etc. and the power booster waveguide

610 are designed for broadband ASE emission, just as in

AHURA-3

the first embodiment (Fig. 10) discussed above. A high

reflectance mirror is provided for each of the seed

waveguides 605A, 605B, 605C, 605D, etc. These mirrors

may be independent of one another, or they may be

5   different sections of a single mirror, such as is shown

in Fig. 15 with the high reflectance mirror 620. The

reflectivity profiles of the high reflectance mirror

for each seed waveguide 605A, 605B, 605C, 605D, etc.

are optimized to provide the correct seed light profile

10   for control of the output ASE spectrum. The power

booster waveguide 615 includes an angled end 625 and an

anti-reflectance coating 630 at its output end.

Spectrum function controls such as tilt can be achieved

through the appropriate mix of seed light functions.

15   Preferably, each one of the wavelength seeds 605A,

605B, 605C, 605D, etc. generate a low power optical

seed signal which differ in center wavelength from one

another and are approximately 5 nm in spectral width.

The low power optical seed signals, which are

20   preferably in the range of 1-20mW, are power combined

by broadband combiner 610 into long single-mode high-

power "booster" waveguide 615 which amplifies the seed

AHURA-3

signals to higher optical power signals, which are

preferably greater than 200 mW. The optical output has

a single spatial mode and is linearly (TE) polarized,

preferably greater than 20 dB. Additionally, the

5   output will exhibit a relative-intensity noise

performance rivaling that of a distributed-feedback

(DFB) laser (<-140 dB/Hz).   Through varying the bias

current to each of N seed amplifier waveguides 605A,

605B, 605C, 605D, etc., the spectral output can be

10   dynamically tailored.

Several preferred embodiments of the present

invention are described herein below which relate to

the waveguide seed section 605 and power booster

amplifier waveguide 615, the broadband N x 1 power

15   combiner 610, and the method of seed-wavelength control

are described in more detail hereinbelow.

SEED & Power Booster Amplifier Waveguides

20   The wavelength seed section 605 of the device 600

is comprised of a parallel array of active

semiconductor waveguides 605A, 605B, 605C, 605D, etc.

AHURA-3

The gain profile within each waveguide is engineered to provide ASE in a particular wavelength range when electrically biased above transparency. It is important to have a high modal gain (both g & Γ) to allow efficient generation of ASE and coupling of the ASE into the waveguide mode for amplification. The desired design parameter optimization needed for seed amplifier waveguide 605A, 605B, 605C, 605D, etc. is similar in nature to that needed for conventional semiconductor optical amplifiers. Preferably, a high reflecting narrowband filter 635 is used to capture, spectrally shape, and redirect the fraction of ASE traveling in the waveguide away from the power booster. The spectral profile of mirror 620 is designed to provide the desired center wavelength and spectral width of the ASE spectrum at the input of the power booster waveguide 615. Each wavelength seed section has an independent p-side electrical contact so as to allow dynamic tailoring of the seed light spectrum. The output power of the wavelength seed section 605 preferably ranges from 1 to 20 mW.

AHURA-3

The power booster section 615 is designed to amplify the ASE light from seed waveguides 605A, 605B, 605C, 605D, etc. which generate power in excess of 200 mW. The design optimization needed for the power booster 615 is complimentary in nature to that required for high power, i.e., greater than 400mW, telecomunication lasers. See, for example, (1) Garbuzov D., *et al.*, (2002). 14xx nm DFB InGaAsP/InP pump lasers with 500 mW CW output power for WDM combining. Optical Fiber Communications Conference, Anaheim, CA; and (2) Tsukiji N., *et al.*, (2001). Recent progress of high power 14xx nm pump lasers. SPIE ITcom on Active and Passive Optical Components for WDM Communication, Denver, CO. It is desirable to use a waveguide optimized for low loss rather than high gain. Waveguides with a modal loss of less than 2 cm^{-1} are generally utilized. This is accomplished by reducing the number of quantum wells, reducing the optical confinement factor, and utilizing asymmetric confinement where the modal overlap is larger over the n-doped cladding than the p-doped cladding. Additionally, a long cavity reduces the devices voltage

AHURA-3

drop and allows a lower dopant concentration to be used for reduction of free carrier absorption loss. For example, this cavity may extend several millimeters.

Furthermore, the quantum wells provide gain across the entire wavelength range of the seed light signals. In a preferred embodiment of the present invention, this is accomplished by chirping the thickness of the quantum wells in the growth direction. For example, the upper quantum well provides shorter wavelength gain while the lower two quantum wells provide longer wavelength gain.

Referring still to Fig. 15, and in a preferred embodiment of the present invention, an angled waveguide 625 is used at the output of the power booster followed by an antireflection coating 630 on the semiconductor facet. This combination is used to reduce feedback into the power booster to less than -60dB and thus prevent distortion of the broadband spectral profile from Fabry Perot interference. The output will be highly linearly polarized because of the polarization dependence of the quantum well gain.

AHURA-3

Preferably, angled waveguide has an angle of about
8°-13°.

High power ASE is achieved by using discrete seed
waveguides 605A, 605B, 605C, 605D, etc. together with
booster amplifier waveguide 615. Device 600 is able to
provide ASE power output in excess of 250mW with a
spectral full-width at half-maximum of 20 nm.

Power Combiner

Power combiner 610 is used rather than a
wavelength combiner to guide seed light to booster
waveguide amplifier 615 for at least two reasons. One
reason is the tremendously challenging complexity for
fabrication of a spectrally flat-top and broadband
wavelength multiplexer, such as a multicavity Arrayed
Waveguide Grating (AWG). Integrated wavelength
multiplexing is also unfeasible due to concerns of
optical feedback to the seed waveguides as well the
large surface area requirements.

Many applications rely on wavelength combiners due
to the inherent 1/N splitting loss of a power combiner.
This intrinsic loss has minimal impact on device 600 as

AHURA-3

the power booster will be operating in a power

saturated regime. A total input power of only several

miliwatts to booster waveguide 615 is needed to deliver

in excess of 200 mW of output power. The use of power

combiner 610, such as a multimode interferometer (MMI)

coupler, is ideal for device 600 in that the MMI has

relaxed requirements on the excess loss, broad spectral

performance, and provides a high return loss. See, for

example, Okamoto, K. (2000). Fundamentals of Optical

Waveguides. San Diego, Academic Press. Low loss can be

achieved in the interference region of MMI though

either (1) quantum-well intermixing, (2) epitaxial

regrowth, or (3) electrical bias to transparency. See,

for example, (1) Holonyak, N. (1998). "Impurity-induced

layer disordering of quantum-well heterostructures:

discovery and prospects." IEEE J. Tpcs. Quantum

Electron. 4(4) 584-594; (2) Kudo K., et al. (2000).

"1.55 μm wavelength-selectable microarray DBF-LDs with

monolithically integrated MMI combiner, SOA, and EA-

modulator." IEEE Photon. Technol. Lett. 12(3); and (3)

Hamamato K., et al., (2002). High-power with low

electric power consumption 1.45 μm active multi-mode

AHURA-3

interferometer laser diode for fiber amplifier

applications. Optical Fiber Communications Conference,

Anaheim, CA.

5   Seed Wavelength Control

A host of technologies are available in the

fabrication of a wavelength control mechanism 635.

Referring still to Fig. 15, and in a preferred

embodiment of the present invention, an approximately

10   5 nm narrow-band high-reflecting mirror can be created

through incorporation of an etched multicavity Bragg

reflector along seed waveguide ridge 605A, 605B, 605C,

605D, etc. The multicavity design can be achieved with

properly-designed phase masks, which are.

15   holographically imprinted on the waveguide directly

through standard lithography methods. The pattern

transfer is preferably achieved through inductively

coupled plasma reactive ion etching process.

Referring now to Fig. 26, and in preferred

20   embodiment of the present invention, wavelength control

mechanism 635 for wavelength seeds 605A, 605B, 605C,

605D, etc. comprises a combination of a series of

AHURA-3

multicavity narrow-band notch filters 640A, 640B, 640C, 640D, etc. and high reflectivity feedback mirrors 645A, 645B, 645C, 645D, etc. Multicavity narrow-band notch filters 640A, 640B, 640C, 640D, etc. are disposed at a

5   45° angle relative to mirrors 645A, 645B, 645C, 645D, etc., respectively. In this approach, thin film coatings disposed on mirrors 645A, 645B, 645C, 645D, etc. are configured to create a 5 nm flat-top transmission peak.

10

In a preferred embodiment of the present invention, integrated semiconductor device 600 is capable of generating over 200 mW of fiber coupled power across a spectral range of 1400-1500 nm with 4 or

15   more spectral controls of the emission profile. Each of the spectral controls has 5 nm resolution. This preferred embodiment of the present invention relies on multicavity thin-film filters 640A, 640B, 640C, 640D, etc. for assembly on a micro-optical bench. Specific

20   steps to create this preferred embodiment of the present invention are discussed hereinbelow.

AHURA-3

A first step comprises amplifier waveguide design and growth. This step involves determining the appropriate epitaxy structure through simulation and experiment to provide suitable broadband gain, and high power. A single non-integrated booster and seed waveguide are demonstrated.

A second step comprises integrated coupler design. This step involves the design of an MMI active/passive (4 x 1) power combiner for integration with the seeds and booster waveguides. Optical isolation, broadband performance, excess loss, and fabrication methods are simulated.

A third step comprises integrated coupler growth and fabrication. This step involves the growth, fabrication, and characterization of an (4 x 1) MMI active/passive coupler.

A fourth step comprises seed wavelength control. This step encompasses the exploration of various technologies for creating the required narrow-band reflector. Source demonstration may rely on thin-film deposited multi-cavity flat-top 5 nm FWHM bandpass filters.

AHURA-3

A fifth step comprises integration, assembly, and characterization. This step involves taking the results of the previous steps and integrating for demonstration and characterization on a micro-optical bench. Power, Spectral Controllability, and Relative Intensity Noise (RIN) are characterized.

A fifth step comprises analysis and optimization. This final step involves systematic study of the results and preparation of fully-integrated sources.

Amplifier Waveguide Design & Growth

While a full rate-equation analysis is needed to precisely predict and determine the expected amplifier waveguide performance, the dependence of the design parameters for the seed and booster waveguides can be illustrated through consideration of power conservation. It can be shown that the output ASE power from a self-generating seed amplifier waveguide is proportional to,

$$P_{ASE}^{Seed} \propto \beta \left(\frac{I}{l} \right) \frac{e^{\Gamma g l}}{g} , \qquad (1)$$

AHURA-3

where β is the spontaneous emission factor, Γ is the
optical confinement factor, g is the material gain, I
is the injected current, and l is the seed's length.
Large modal gain and and a high spontaneous emission
factor are desirable. For the booster waveguide, the
limiting maximum power is given by,

$$P_{ASE}^{Booster} \propto \frac{IV_g\eta - P_{out}^{spon} - P_{heat}^{auger}}{\alpha_{total}\Delta l}, \qquad (2)$$

where η is the internal quantum efficiency, P_{out}^{spon} is the
optical power from spontaneous emission, P_{heat}^{auger} is the
power dissipated from nonradiative recombination, V_g is
the active region bandgap voltage, I is the injected
current, and l is the incremental (saturated) length of
the booster. This equation shows that minimization of
the total loss, rather than high gain, is desired.

To facilitate on chip integration and eliminate
the potential need for epitaxial regrowth, the booster
waveguide structure can also be used for the seed
waveguide structure by increasing the length of the
seed. However, this increases die length, and thus
effects power consumption, yield, and ultimately cost.

AHURA-3

To achieve ASE emission and gain over an extended bandwidth (100 nm), a chirped quantum well design is employed. This is accomplished through varying the thickness of the quantum wells in the growth direction.

5 For example, the upper quantum well provides shorter wavelength gain while the lower two quantum wells provide longer wavelength gain. A solid model will be used for gain curve simulations.

As can be observed from Equation 2, modal loss in

10 the amplifier waveguide is an important design parameter. Great care is taken to properly optimize this parameter. The impact of reducing doping concentration on voltage should also be considered. A technique has been developed to achieve an asymmetric

15 confinement factor. Asymmetric confinement is used to reduce the mode's overlap with the heavily absorptive p-doped region. Booster amplifier waveguides 615 having less than 2 cm^{-1} (total loss) can be achieved using this technique. This technique will further be

20 optimized in a preferred embodiment of the present invention so as to reduce active amplifier waveguide losses for our proposed device to below 1 cm^{-1}.

AHURA-3

Referring now to Fig. 16, and in a preferred
embodiment of the present invention, there is shown a
simulated transverse mode shape 650 of an asymmetric
optical confined ridge waveguide 655 of booster

5   waveguide 615 (Figs. 15 and 21).

Referring now to Fig. 17, an extremely important
design consideration is thermal management. Often the
first limits observed for output power are due to
thermal roll over. Finite element techniques may be

10   used to simulate and design the structure's thermal
impedance. Looking at Fig. 3, there is shown a
temperature distribution 660 for booster waveguide 615
(Figs. 15 and 21). The calculated thermal impedance is
greater than 7°/W for a 4 mm device.

15

Integrated Coupler Design

An MMI power combiner will be used to guide the
light from the seed waveguides to the booster
waveguide. MMIs have the unique properties of low

20   insertion loss, large optical bandwidth, compact size,
polarization insensitivity, low cross talk, and
forgiving fabrication tolerances. (See, for example,

AHURA-3

Okamoto, K. (2000). <u>Fundamentals of Optical Waveguides.</u>
San Diego, Academic Press.) A design schematic of a
typical MMI power combiner 665 is shown in Fig. 18.
Using guided mode propagation analysis, (see Soldano,

5   L.B., et al. (1995). "Optical multimode interference
devices based on self-imaging: principles and
applications." <u>J. Lightwave Technol.</u> 13:615-627) the
dimensions of the MMI as shown in Fig. 18 are chosen to
satisfy self-imaging. The influence of waveguide loss

10   on coupler performance are extensively parameterized.
This result together with the outcome of the
fabrication considerations of the step comprising the
integrated coupler growth and fabrication determine the
final MMI design.

15   Several substeps are performed to complete the
integrated coupler design. These substeps include
simulation/calculation using BPM, FDTD, and analytic
techniques of the excess loss, return loss to seed and
booster, spectral dependence of the coupling

20   coefficient, and output mode shape. The substeps also
comprise parameterization of the effect of waveguide
loss and finalization of dimensions and layer structure

AHURA-3

using considerations from the step of the integrated
coupler growth and fabrication.

Integrated Coupler Growth & Fabrication

5   The MMI coupler 665 will be grown in the
InP/InGaAsP material system using a MOCVD. Coupler 665
is preferably fabricated using conventional wafer
processing techniques. Coupler 665 is fabricated using
InP-based materials through optical lithography and
10   wet/dry etching processes. Referring now to Fig. 19,
there is shown a wet-etched InP based ridge waveguide
670 in a SEM micrograph.

The interference region of the MMI 665 must have
low loss. This presents challenges in achieving the
15   integration of the active seed waveguides 605 and
booster waveguides 615 with power combiner 610, such as
MMI 665. There are two approaches for achieving low
loss. These include quantum-well intermixing, see
Holonyak, N. (1998). "Impurity-induced layer
20   disordering of quantum-well heterostructures: discovery
and prospects." IEEE J. Sel. Tpcs. Quantum Electron.
4(4):584-594, and electrical bias to transparency, see

AHURA-3

Hamamoto K., et al., (2002). High power with low
electric power consumption 1.45 μm active multi-mode
interferometer laser diode for fiber amplifier
applications. Optical Fiber Communications Conference,
5   Anaheim, CA.

       The selection of the approach is made through
analysis of the simulation results of the integrated
coupler design together with the results of initial
intermixing experiments.

10   Intermixing can be used for spatial bandgap tuning
of multiquantum well structures, see, for example, Si,
S.K., et al., (1998). "Area selectivity of InGaAsP-InP
multiquantum-well intermixing by impurity-free vacancy
diffusion." IEEE J. Sel. Tpcs. Quant. Elect. 4(4) 619-
15   623. Impurity-free vacancy diffusion (IFVD) benefits
from low scattering loss, see Si, S.K., et al., (1998).
"Area selectivity of InGaAsP-InP multiquantum-well
intermixing by impurity-free vacancy diffusion." IEEE
J. Sel. Tpcs. Quant. Elect. 4(4) 619-623. Vacancy
20   intermixing can be achieved through implantation of
double-charged phosphorus ions (P++) in the layers
above the quantum well active region. See, for

AHURA-3

example, Paquette, M. *et al.* (1998). Blueshifting of InGaAsP-InP laser diodes using a low energy ion-implantation technique." IEEE J. Sel. Tpcs. Quant. Elect. 4(4): 741-745. Point defects are generated that

5 are able to thermally diffuse and contribute to intermixing when annealed. The bandgap of the resulting intermixed material shifts to higher energy by more than 80 nm, i.e., near 1480 nm. The intermixed material exhibits similar photoluminescence intensity

10 to that of the non-implanted material. Lasers with excellent slope efficiency and threshold have been fabricated using intermixed material. See, for example, Paquette, M. *et al.* (1998). Blueshifting of InGaAsP-InP laser diodes using a low energy ion-

15 implantation technique." IEEE J. Sel. Tpcs. Quant. Elect. 4(4): 741-745; and Yu, S.F., *et al.* (1998). "Semiconductor lasers using diffused quantum-well structures." IEEE J. Sel. Tpcs. Quant. Elect. 4(4): 723-735. This method of vacancy diffusion is utilized

20 for shifting the bandgap in the interference region of the MMI to avoid optical absorption.

AHURA-3

Several substeps are preferably performed during· integrated coupler growth and fabrication. One substep is fabrication of waveguide lasers with intermixed material. This is followed by evaluation of the internal loss and the internal quantum efficiency. A freeze fabrication approach may also be used.

Seed Wavelength Control

Referring now to Figs. 15 and 20, and in a preferred embodiment of the present invention, narrow-band, high-reflecting mirror 620 is created by incorporating a multicavity Bragg reflector etched along the ridge of seed waveguide 605A, 605B, 605C, 605D, etc. The multicavity design is achieved with a properly-designed phase mask, holographically imprinted on the waveguide 605A, 605B, 605C, 605D, etc. through standard lithography methods. The pattern transfer can be achieved through an inductively-coupled-plasma reactive-ion-etching process.

Looking at Fig. 20, there is shown a holographic lithography technique 675. A Karl Suss MA6 lithography

AHURA-3

system is fitted with a near field holographic adapter
to create holographic lithography technique 675.

The 0 beam 680 and -1 beam 685 are used to create
interference patterns 690 on waveguides 605A, 605B,

5   605C, 605D, etc. The 0/-1 order principle is
advantageous for fine-pitch applications that require
suppression of unwanted orders. In this geometry,
incident light 695 is diffracted partially into the -1
order 685. Self-interference between the -1 order 685

10   and the undiffracted zero order beam 680 creates an
interference pattern 690 with a pitch equal to the
phase mask pitch. This approach is advantageous over
conventional +1/-1 order phase mask as +1 order beam
can degrade the grating formation, and hence influence

15   its optical characteristics.

Referring now to Fig. 21, and in a preferred
embodiment of the present invention, holographic
grating technique 675 is implemented for "on-chip"
wavelength control for further scaling of the number of

20   seed guides 605. This relies on the use of external
thin-film filters 640A, 640B, 640C, 640D, etc. for
wavelength control of seeds 605A, 605B, 605C, 605D,

AHURA-3

etc., respectively. Dielectric notch filters 640A, 640B, 640C, 640D, etc. and high reflecting feedback mirrors 645A, 645B, 645C, 645D, etc. are used in combination with one another, respectively.

5   The multi-cavity and high reflective thin films can be deposited by an Ion Tech Spector ion beam sputtering system. An optical monitoring system ensures accurate coatings to meet the technical requirements. Proper glass substrate ensures athermal

10   properties of the coating.

Looking at Fig. 22, there is shown simulated transmission 700 of a multicavity thin notch filter 640A, 640B, 640C, 640D, etc. used for seed wavelength control. Multicavity thin notch filters 640A, 640B,

15   640C, 640D, etc. are designed as a narrow band filter about 5nm wide and centered at 1450 nm.

Several substeps are preferably performed for creating seed wavelength control. These substeps include the evaluation of the holographic imprinting

20   technique for etching of multicavity semiconductor Bragg gratings, the design and deposit thin-film filters for off-chip wavelength control, and the

AHURA-3

provision of prototype thin-film wavelength control of a single seed waveguide.

Integration, Assembly, & Characterization

Integration and assembly of device 600 occurs after (1) amplifier waveguide design and growth, (2) integrated coupler design, (3) integrated coupler growth and fabrication, and (4) seed wavelength control. Seed array 605 is first fabricated with MMI coupler 610 and output of MMI 610 is characterized for power, mode shape, spectral distribution, and RIN. Information from these measurements is then used to feedback and iterate the process where required. Booster 615 is then fabricated after MMI 610. The semiconductor die 705 is then be bonded to an AlN carrier and actively aligned on an AlN platform to lens array 710 and thin film filters 640A, 640B, 640C, 640D, etc. The optical performance is then tested.

Several substeps are preferably performed during integration, assembly and characterization. These substeps include fabrication of seed array 605 with MMI coupler 610; characterization of performance of device

AHURA-3

600, including power, mode shape, spectral
distribution, & RIN; and iteratation of the
process/design as required. Next, these substeps
include fabrication of a complete device 600 and

5   characterization of its performance by assembling it
together with thin-film filters for stabilization on
micro-optical bench, and then characterization of
device 600 performance including power, mode shape,
spectral distribution, & RIN.

10   Referring again to Figs. 14(a) and 14(b), and as
discussed hereinabove in the section "6.2.2.5 Fifth
Embodiment", non-integrated seed and booster amplifier
waveguides are used to generate high power ASE. The
seed wavelength generated by discrete seed 505 is not

15   controlled by a spectral filter nor are the active
regions of the amplifier waveguides engineered to
provide an extended gain bandwidth of greater than
50 nm as described in this preferred embodiment of the
present invention.

20   The output ASE power in this preferred embodiment
of the present invention is nearly three times higher
than the highest known report achieved from a

AHURA-3

single-mode semiconductor waveguide (see, for example,

Cho, S.H., *et al.* (2001) "90 mW CW superluminescent

output power from single-angled facet-ridge waveguide

at 1.5 μm." <u>Trends in Optics and Photonics Series</u> 31)

5   and more than ten times that of any comparable

commercial product (e.g., several telecommunication

instrumentation suppliers market broadband single-mode

fiber-coupled semiconductor LED sources for use in

passive WDM component characterization with output

10   powers in the range of 0 to 10 mW).

    Referring now to Fig. 23, and in a preferred

embodiment of the present invention, there is shown a

plot 715 of the measured light-verses-current

performance obtained using device 600 having a discrete

15   seed array 605 and booster 615 for ASE generation. In

this preferred embodiment of the present invention,

more than 250 mW of ASE power is generated by the ASE

source 500. The seed input power is approximately 3 mW

and the measured ASE spectrum has a full-width

20   half-maximum (FWHM) of 20 nm.

    Referring now to Fig. 24, there is shown the

measured ASE spectrum 720 from booster waveguide 615 at

AHURA-3

100 mW of output power. Similar spectra output is produced at the maximum output power. The RIN spectrum of this source is less than -140dB/Hz from 100 Hz to beyond 15 GHz.

5

7.0 Modifications

A system and method have been disclosed for amplifying optical signals such as those used in telecommunication systems, HFC-CATV applications, and

10   other instrumentation and imaging applications. A system and method for producing a high power broadband light source from ASE have also been disclosed, where the high power broadband light source may be used for amplifying optical signals or for other purposes, e.g.,

15   general instrumentation (including, for example, fiberoptic gyros), imaging (including, for example, medical imaging, and semiconductor analysis applications). While various preferred embodiments have been described and shown, it will be understood

20   that there is no intent to limit the present invention by such disclosure but, rather, it is intended to cover

AHURA-3

all modifications and alternate constructions falling

within the spirit and scope of the invention.

AHURA-3